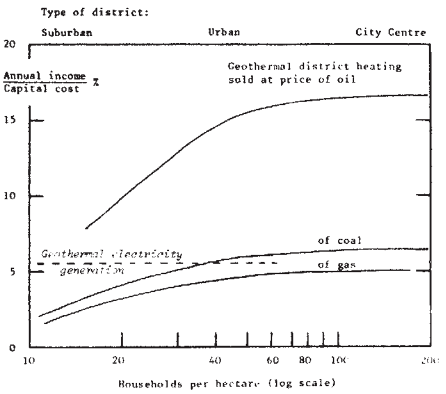

How return on capital for a geothermal district heating scheme varies according to the household density and the equivalent fuel price.

geothermal source temperature and T_1 is the temperature at which the geothermal fluid is reinjected into the aquifer. α is an empirical constant which is determined by the losses in the power cycle and we take the value $\alpha = 0.6$[8]. For $T_2 = 373$ K, $T_1 = 308$ K and $T_0 = 298$ K, $\eta = 0.073$ and the gross electrical output is 1 MW per doublet. The capital cost of the plant is £754,000[8] and the cost of the boreholes and connections to the central plant is £1.34M per doublet. Total capital is thus £2.09M for a net electrical output of 750 kWe. Operating at an 80% load factor this entrepreneur is able to sell some 5.3×10^6 kWh each year to the utility worth £116,000 at the current price of 2.2p per kWh paid by the Electricity Council's Area Boards. The return on capital is 5.5% per year.

Relative and absolute merits of the applications

Of the two schemes, electricity generation would have a higher return on capital if the price at which the other sold heat were determined by gas, for all dwelling densities. For a density of 40 households per hectare it would require an increase in the price of gas by 30% with the electricity price unchanged for district heating to hold the advantage. On the other hand, if the price of heat were fixed by oil, district heating would provide the better investment for densities greater than 12 households per hectare. The relative merit of the schemes is not sensitive to the assumed temperature of the aquifer.

It should be noted that we have stacked the odds in favour of district heating, in three respects particularly. First, the boreholes are assumed to be within the district they serve. Heat transmission would materially raise the capital cost of the scheme. Second, we have included no 'overheads' allowance for the district heating scheme. For the electricity scheme most of these costs are included in the difference between the Area Board's buying and selling price for electrical energy. Third, we have assumed (with refs 5 and 7) 100% market penetration. To achieve this, district heating would in fact have to set its price considerably below that of competing fuels.

Neither of the schemes is particularly attractive in absolute terms; but should energy prices as a whole increase relative to other costs this particular conclusion could well be reversed. In a regime under which a large proportion of electricity is generated from fossil fuels, major relative changes in electricity and fossil fuel prices seem unlikely.

We conclude that the generation of electricity from low grade heat is at least as likely to become an attractive proposition as the provision of geothermal district heating in countries which, like Britain, generate a large proportion of their electricity from fossil fuels. Paradoxically, the geothermal electricity option saves money but wastes fossil fuels: we suspect that none but the most high minded will be put off.

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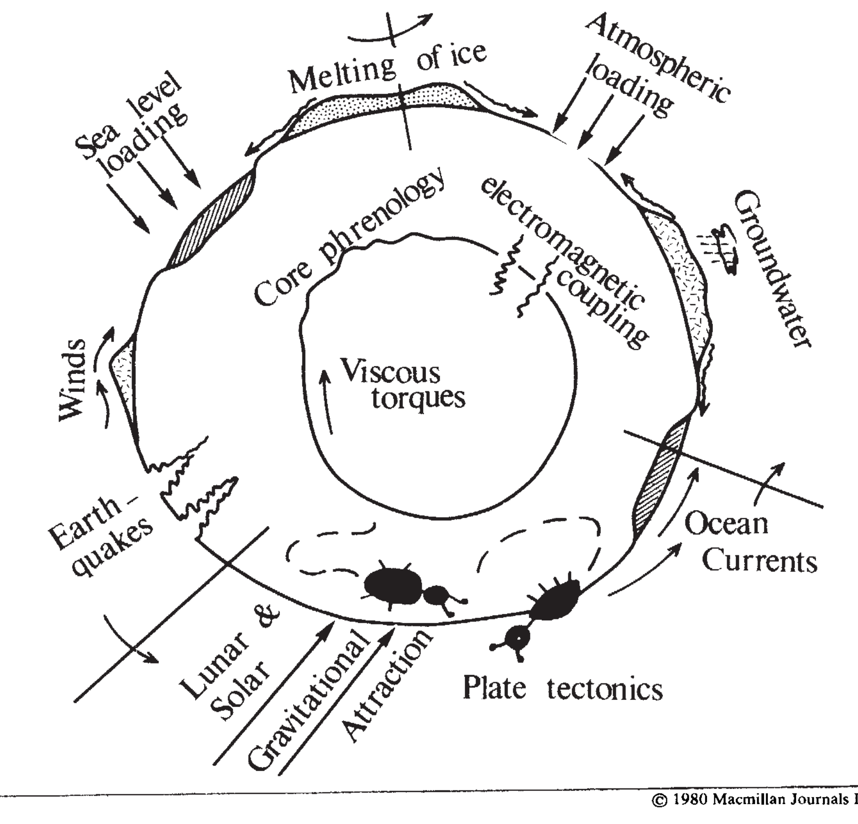
Changes in length-of-day and atmospheric circulation

from Kurt Lambeck

OBSERVATIONS reported in this issue of *Nature* (Hide *et al.* p141) show that zonal components of atmospheric momentum contribute to high frequency changes in the length-of-day.

For many years astronomers have observed fluctuations in the Earth's rate of rotation — or changes in the length-of-day — that are attributable to various forces acting on the Earth's mantle and to a redistribution of mass within the Earth, oceans and atmosphere. Despite the smallness of these departures from uniform rotation — changes in length-of-day of about 10^{-3} s typically occur over time intervals of a few days to several years, and changes of about 10^{-2} s occur over several decades — they have intrigued geophysicists for many years and a complete discussion requires one to delve into atmospheric and oceanic circulation problems, into the Earth's elasticity and anelasticity and into magnetohydrodynamics of the core[1,2] (Fig. 1). Astronomers measure the integrated amount τ by which the Earth is slow or fast

Fig. 1 Schematic illustration of the forces that perturb the Earth's rotation. Topographic coupling of the mantle to the core has been referred to as 'Core Phrenology' by R.R. Hide while the beetles, following T. Gold, represent the effect of continental drift.



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after a certain time interval by comparison with a uniform time scale and the first derivative of this function gives a measure of the change in the length-of-day. Figure 2 illustrates the spectrum of the proportional changes in the length-of-day. Present techniques give accuracies for τ of about 1.5×10^{-3} s for an integration time of about 5 days[3] but new observational techniques based on laser range measurements to artificial satellites or to the Moon and long-baseline radio-interferometry have been developed. Preliminary results[4,5] indicate that improvements in resolution and precision are imminent.

We can anticipate that a new part of the length-of-day spectrum will rise above the measurement noise level (see Fig. 1). For example, rapid changes in length-of-day may occur in conjunction with very large earthquakes, similar to the Chandler wobble problem[6,7], in which the direction of the rotation axis is displaced relative to the Earth's crust when large earthquakes occur. Such changes will only be evident if there is no 'meteorological noise' in the length-of-day data or if the meteorological contribution to the length-of-day changes can be reliably evaluated from the meteorological data.

The contribution of the atmosphere to the broad spectrum of rotation perturbations has long been recognized as being important. A satisfactory quantitative comparison of the zonal angular momentum computed from wind data with astronomical observations was made only relatively recently[8] but it is now recognized[9] that variations in length-of-day with frequencies between about 0.2 cycles yr^{-1} and 4 cycles yr^{-1} are mainly a consequence of an exchange of angular momentum between the Earth and the atmosphere. This conclusion was substantiated by Lambeck and Hopgood in a recent compilation of ten years of zonal angular momentum[10]. At higher frequencies (i.e. $\gtrsim 4$ cycles yr^{-1}) the atmosphere may contribute significantly to the length-of-day spectrum[1,9]. A quantitative comparison of the length-of-day observations with the zonal winds in this frequency range has now been attempted by Hide and co-workers, (this issue of *Nature* p141) based on data collected in 1979 during the first CARP Global Experiment.

Hide *et al.* have attempted to evaluate the zonal component of the angular momentum of the atmosphere at 12 hourly intervals using wind and pressure data collected during two 8 week periods in 1979. Where observations were incomplete they were supplemented by values deduced from numerical circulation models. A comparison with the astronomical length-of-day data, particularly for the second period, indicates a generally good agreement and confirms that the atmosphere makes a significant contribution to the high frequency changes in length-of-day. In particular, observed changes in length-of-day over five day periods can be attributed to rapid exchanges of angular momentum between the solid Earth and the atmosphere. From Hide *et al.*'s Fig. 3 it is also clear that shorter period, atmospherically induced, changes in rotation can be anticipated when the new methods of observing the rotation are fully exploited. What Hide *et al.*'s results show is that for precise and high-resolution length-of-day observations to be of geophysical use, the zonal wind field must be globally known with an accuracy and resolution that is at least as good as that collected during the first CARP Global Experiment. Such a major undertaking is justifiable for meteorological reasons. If future work substantiates Hide *et al.*'s conclusion then it may also become possible to use the high frequency and irregular length-of-day fluctuations as global contraints in numerical modelling of the circulation and, in particular, this may lead to a better understanding of how the atmospheric torques are distributed over the Earth's surface.

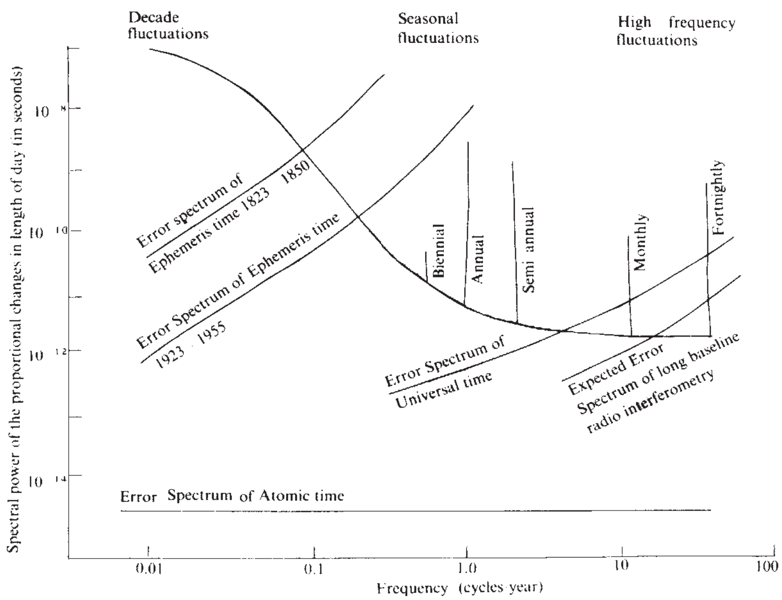

Fig. 2 Schematic spectrum of the proportional changes in length-of-day based on astronomical observations taken since the early nineteenth century. The error spectrum of Universal time is that which can be attained with astronomical observations since the introduction of atomic time. The error spectrum of ephemeris time is appropriate to the older data for the indicated time-intervals.

Towards the other end of the length-of-day spectrum, meteorological influences do not appear to be very important[1,10] although some contribution cannot be excluded. Recently it has been suggested by Currie[12] that there is an 11 year length-of-day fluctuation associated with the solar cycle. Such a suggestion has been made previously[13] but this conclusion is hard to reconcile with the quality of the earlier astronomical data. For example, prior to 1850 the astronomical data becomes only barely significant when averages are taken over 10 years while from 1923–55 only 5 year averages are significant (Fig. 2). Only since the introduction of atomic time in 1955 can one be certain that fluctuations with about 10 year periods will reflect real changes in rotation. This being said, a relation between solar activity and the Earth's rotation cannot be dismissed if there is a solar influence on the zonal circulation as was suggested most recently by Nastrom and Belmont[14]. Attempts at evaluating the contribution of the atmosphere to long period length-of-day variations have not been wholly successful through lack of complete and reliable meteorological data but they do indicate that the winds can contribute at most about 10–20% to the decade length-of-day fluctuations[1,10].

Partly by an elimination process, core-mantle coupling processes[1,15] remain the most likely contenders for these decade fluctuations but here, as at the higher frequencies, the atmospheric contributions should be eliminated before other geophysical mechanisms can be reliably evaluated. Hide *et al.*'s results shows that this indeed can be done. □

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